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1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE March 22, 2000	3. REPORT TYPE AND DATES COVERED Final Progress Report-04/01/96-03/31/00

4. TITLE AND SUBTITLE A Study of Turbulence and Dispersion in the Atmospheric Boundary Layer Above Heterogeneous Land Surfaces	5. FUNDING NUMBERS DAAH04-96-1-0044
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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSORING / MONITORING AGENCY REPORT NUMBER ARO 34718.8-EV

11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION / AVAILABILITY STATEMENT

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13. ABSTRACT *(Maximum 200 words)*

The major objective of this study was to better understand the physical mechanisms involved in the dispersion of materials in the ABL that develops above heterogeneous land surfaces, using large-eddy simulations. This project consisted of three tasks: (i) An evaluation of our LES model against observations; (ii) A systematic analysis of the impact of microscale and meso-γ-scale heat patches and topographical features on the structure of the ABL; and (iii) An analysis of the impact of these landscape heterogeneities on the dispersion of materials in the ABL. All three tasks have been fully completed. Using radiosondes, a network of surface fluxes, and a volume-imaging lidar deployed in FIFE, we showed that, overall, the LES model performs quite well. However, its subgrid-scale parameterization needs to be improved to increase eddy dissipation. Various simulations using the FIFE data sets as well as ideal conditions indicate that microscale heterogeneities of surface heat fluxes and topographical features have only a minor to modest impact on the CBL, but can significantly affect the structure of turbulence. Meso-γ-scale heterogeneities not only affect the structure of turbulence, but they can also significantly affect the mean characteristics of the CBL. These heterogeneities can also significantly affect the dispersion of materials. The results of this research were published in major peer-reviewed journals, and were presented at various professional meetings. A fourth and last year of funding was also provided to make a preliminary analysis of the ability of RAMS to simulate the stable nocturnal boundary layer (SNBL), in preparation of a more complete study on the dispersion of materials in this type of boundary layer, which will be proposed as a continuation of this completed project.

14. SUBJECT TERMS 1. Large-eddy simulations in complex terrains 2. Lagrangian dispersion particle modeling in complex terrains	15. NUMBER IF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500 Enclosure 1 Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18

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A STUDY OF TURBULENCE AND DISPERSION IN THE ATMOSPHERIC BOUNDARY LAYER ABOVE HETEROGENEOUS LAND SURFACES

FINAL PROGRESS REPORT

Grant Number: **DAAH04-96-1-0044**

Submitted to the

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March 24, 2000

Contents

1 Problem Studied

The structure of the eddies in the atmospheric boundary layer (ABL) that develops above heterogeneous land surfaces seems to be significantly affected by the spatial distribution of the land-surface sensible heat flux, and by topography. This is expected to have an important impact on the dispersion of materials (*i.e.*, gases, aerosols, and other particles) in the ABL.

The research project conducted here consisted of three tasks, which were performed with the Colorado State University - Regional Atmospheric Modeling System (RAMS), a state-of-the-art modeling system designed to support basic research in the atmospheric sciences: (i) An evaluation of the Large-Eddy Simulation (LES) option of RAMS (hereafter referred as "RAMS-LES") using the the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) data sets; (ii) A systematic analysis of the impact of microscale and meso-γ-scale heat patches and topographical features on the structure of the ABL with the RAMS-LES; and (iii) An analysis of the impact of these landscape heterogeneities on the dispersion of materials in the ABL. This third task was performed with the Lagrangian Particle Dispersion Model (LPDM) option of RAMS "fed" with the atmospheric conditions generated by the large-eddy simulations performed under Task 1 and Task 2.

This study contributes to a better understanding of the physical mechanisms involved in the dispersion of materials in the ABL that develops above heterogeneous (realistic) land surfaces. In addition, the impact of land-surface heterogeneity on the mean atmospheric variables in the ABL provides new insights on the representation of the ABL in atmospheric models which do not have the very-high grid resolution required to resolve turbulent eddies.

2 Summary of the Most Important Results

2.1 Model Validation

As part of Task 1, the RAMS-LES was used to simulate the convective boundary layer (CBL) that developed on July 1, 1987, over the FIFE domain. Three simulations were produced using different boundary conditions at the ground surface, namely: (i) spatial distribution of topography and spatial distribution of surface heat fluxes; (ii) spatial distribution of topography but mean surface heat fluxes; and (iii) no topography and mean surface heat fluxes. The diurnal variation of mean surface fluxes and their spatial distribution were derived from the FIFE network of observations. In all cases, the model was initialized with the atmospheric sounding observed in this domain at 7 a.m., and run until 3 p.m. The resulting mean profiles of temperature and specific humidity were compared to those observed with

atmospheric soundings at 9 a.m., 10:30 a.m., and 12:30 p.m. The simulated structure of turbulence was qualitatively compared with that obtained from a volume-imaging lidar (VIL) scanning the CBL over the simulated domain, during that day. Power spectra and autocorrelations of mixing ratio were calculated from the model outputs and were compared to those obtained from the VIL.

Overall, the model performed quite well. Observed atmospheric soundings were within 1 K and 1 g/kg of the simulated mean profiles of temperature and specific humidity, respectively, and indicated that the model correctly predicts the CBL height. Similarities in the structure of the eddies obtained from the model and the VIL were clearly identified. Spectral analysis indicated that resolved eddies (*i.e.*, eddies larger than 200 m) are relatively well simulated with the model, but that the energy cascade is not well represented by the Deardorff 1.5-order-of-closure subgrid-scale parameterization. Autocorrelation analysis indicated that the model correctly simulates the characteristic size of the eddies, but that their mean lifetime is longer than that observed with the VIL, indicating a too weak dissipation of the eddies by the subgrid-scale scheme. Thus, this study emphasized the needs to develop better subgrid-scale parameterizations for LES models. The different simulations also indicated that topographical features of the order of 100 m and micro-β scale heterogeneity of surface heat fluxes had only a minor to modest impact on the CBL developing over a relatively humid surface.

A complete description of this evaluation study, including a discussion of the dataset produced by the VIL, is given in Avissar *et al.* (1998). This paper is provided in Appendix A.

2.2 Impact of Landscape Heterogeneity

In addition to the evaluation of RAMS-LES, the above-mentioned numerical experiments indicated that topographical features of the order of 100 m and micro-β scale heterogeneity of surface heat fluxes had only a minor impact on the CBL developing over a relatively humid surface (see Avissar *et al.*, 1998). While these simulations represented real topographical features, they provide only limited insights on the key issue being investigated here, namely the impact of landscape heterogeneity on the ABL.

As part of Task 2, the effects on the CBL of surface heterogeneities produced by various topographical features as well as sensible heat waves with different means, amplitudes, and wavelengths, were investigated. We found that the impact of topography and of heat-wave amplitude and wavelength is nonlinearly dependent upon the mean heating rate. The circulations (or rolls) resulting from surface heterogeneity are relatively strong when the hills dimensions (*i.e.*, the characteristic height and width of the hills) and the heat-wave amplitude and wavelength are relatively large, especially at low mean heating rate. In that case the profiles of horizontally-averaged variables are quite strongly modified

in the CBL. The potential temperature is not constant with elevation, and the sensible heat flux considerably departs from the linear variation with height obtained in a typical CBL that develops over an homogeneous domain. The mean turbulence kinetic energy (TKE) profile depicts two maxima, one near the ground surface and one near the top of the CBL, corresponding to the strong horizontal flow that develops near the ground surface and the return flow at the top of the CBL.

This study is described in detail in Avissar and Schmidt (1998) and Gopalakrishnan *et al.* (2000a), which are provided in Appendix B and Appendix C, respectfully. A third paper, by Baidya Roy and Avissar (2000) resulting from this task summarizes a wavelet analysis of the atmospheric scales resulting from the various characteristic scales of landscape heterogeneity forcing. This paper is provided in Appendix D.

2.3 Impact on Dispersion of Materials

The velocity components resulting from the various runs produced as part of Task 1 and Task 2 were used to "feed" the Lagrangian Particle Dispersion Model (LPDM) option of RAMS, to study the effects of landscape heterogeneity on the dispersion of materials in the CBL. The major findings from the various experiments performed in this study are:

1. The turbulent eddies that develop above a flat ground surface heated homogeneously are randomly distributed within the CBL. Neutrally buoyant materials emitted at ground level of such a domain remain there momentarily, but then quickly "lift-off" towards the middle of the CBL. When released from elevated sources, they first descend towards the ground surface and then move towards the middle of the CBL. While near-surface plumes ascend due to the "sweep out" of particles converging into strong updrafts generated near the surface, elevated plumes are most likely affected by downdrafts, whose area coverage is much larger than updrafts. These results are not new (see *e.g.*, Lamb, 1984; Deardorff 1987; Briggs, 1993), and they are used here to confirm the correct behavior of the model and, mostly, as a reference for the dispersion simulations above heterogeneous domains;

2. Heat flux heterogeneities with a characteristic length scale larger than about 5 km have a remarkable influence on particle dispersion in the CBL. The horizontal pressure gradients created by these heterogeneities impede vertical mixing. For a near-surface release, particles are advected horizontally rather than "lifting-off," increasing the concentration there. Particles released at higher elevations reach the surface much more slowly than when released above a flat, homoge-

neous domain. The weaker the mean sensible heat flux injected in the atmosphere at the ground surface, the more significant is this effect;

3. Hilly terrain has only a modest impact on the vertical mixing of passive materials in the CBL. This is probably because horizontal pressure gradients resulting from small topographical features are weak and, consequently, buoyancy appears to have a stronger control on the dispersion of particles released at lower elevations. This is true even with hills as high as 25% the height of the CBL. However, big hills have a noticeable effect on the dispersion of particles released from higher elevations. In particular, for a source height located at about 25% the height of the CBL, the locus of the maximum concentration in crosswind-integrated plume descends to the surface of the hill noticeably more slowly than above a flat, homogeneous domain.

This study is described in detail in Gopalakrishnan *et al.* (2000b), which is provided in Appendix E.

3 List of Publications Resulting from this Grant

3.1 Articles in Peer-Reviewed Journals

Avissar, R., E.W. Eloranta, K. Gurer, and G.J. Tripoli, 1998. An Evaluation of the Large-Eddy Simulation Option of the Regional Atmospheric Modeling System in Simulating a Convective Boundary Layer: A FIFE Case Study. *J. Atmos. Sci.*, **55**, 1109–1130.

Avissar, R. and T. Schmidt, 1998. An evaluation of the scale at which ground-surface heat flux patchiness affects the convective boundary layer using a Large-Eddy Simulation model. *J. Atmos. Sci.*, **55**, 2666–2689.

Baidya Roy, S., and R. Avissar. Scales of response of the convective boundary layer to land-surface heterogeneity. *Geophys. Res. Lett.*, **27**, 533-536.

Gopalakrishnan, S. and R. Avissar, 2000. Dispersion of passive materials in the convective boundary layer above heterogeneous landscape using large-eddy simulations and a Lagrangian Particle Dispersion Model. *J. Atmos. Sci.*, **57**, 352–371.

Gopalakrishnan, S.G., S. Baidya Roy, and R. Avissar, 2000. An evaluation of the scale at which topographical features affect the convective boundary layer using large-eddy simulations. *J. Atmos. Sci.*, **57**, 334–351.

3.2 Peer-Reviewed Book Chapters

Avissar, R., 1997: At what scales does landscape heterogeneity impact climate? In: *Elements of Change 1997*, S.J. Hassol and J. Katzenberger, Eds., Aspen Global Change Institute, Aspen, Colorado, pp. 34–39 **(Invited Article)**.

3.3 Conference Proceedings

Avissar, R., 1997. Parameterization, boundary conditions, and initialization of atmospheric models: The example of land processes. *Proc. Symposium on Regional Weather Prediction on Parallel Computer Environments*, G. Kallos, V. Kotroni, and K. Lagouvardos (Eds), Athens, Greece, October 15-17, 1997, pp. 67-78.

Avissar, R. and T. Schmidt, 1997. At which scale landscape heterogeneity affects atmospheric dynamics. *77th American Meteorological Society Annual Meeting*, Long Beach, CA, February 2-7, 1997.

Avissar, R., S.G. Gopalakrishnan, and S. Baidya Roy, 1999. An evaluation of the scale at which landscape heterogeneity affects the CBL with large-eddy simulations. *Proceedings of the 13th Symposium on Boundary Layers and Turbulence*, 79th Annual Meeting of the American Meteorological Society, Dallas, TX, January 10-15, 1999, pp. 457-459, **and** *Proceedings of the 14th Conference on Hydrology*, 79th Annual Meeting of the American Meteorological Society, Dallas, TX, January 10-15, 1999, pp. 435-437 (published jointly in both proceedings).

Baidya Roy, S. and R. Avissar, 1999. A wavelet analysis of the scale of response of the CBL to landscape heterogeneity. *Proceedings of the 13th Symposium on Boundary Layers and Turbulence*, 79th Annual Meeting of the American Meteorological Society, Dallas, TX, January 10-15, 1999, pp. 288-290.

Gopalakrishnan, S.G., and R. Avissar, 1999. An analysis of the impacts of land-surface heterogeneity on the dispersion of passive materials in the convective boundary layer using a coupled large-eddy simulation and lagrangian particle model. *Proceedings of the 13th Symposium on Boundary*

Layers and Turbulence, 79th Annual Meeting of the American Meteorological Society, Dallas, TX, January 10-15, 1999, pp. 650-652.

3.4 Abstracts

Avissar, R., 1997. Scaling land-atmosphere interactions. *EOS, Trans. Amer. Geophys. Union*, **78:**136 **(invited)**.

Avissar, R., S.G. Gopalakrishnan, and S. Baidya Roy, 1998. At which Scale Land-Surface Heterogeneity affects the Convective Boundary Layer. *EOS, Trans. Amer. Geophys. Union*, **79:**375.

Baidya Roy, S., S.G. Gopalakrishnan, T. Schmidt, and R. Avissar, 1997. A Wavelet Analysis of the Scales of Response of the Convective Boundary Layer to Land-Surface Heterogeneity. *EOS, Trans. Amer. Geophys. Union*, 78:26.

Gurer, K. and R. Avissar, 1996. Evaluation of RAMS-LES using FIFE dataset. *EOS, Trans. Amer. Geophys. Union*, **77:**116.

Peters-Lidard, C.D., R. Avissar, and E.F. Wood, 1997. The impact of spatial heterogeneity of landscape on the structure of the atmospheric planetary boundary layer in Little Washita. *77th American Meteorological Society Annual Meeting*, Long Beach, CA, February 2-7, 1997.

3.5 Presentations

Avissar, R., 1996. *Evaluation of RAMS-LES using FIFE dataset.* Spring Meeting of the American Geophysical Union, Baltimore, Maryland, May 20-24, 1996.

Avissar, R., 1996. *Which type of observations are needed to evaluate high-resolution atmospheric models: A FIFE case study.* Data Assimilation Branch, NASA Goddard Space Flight Center, Laboratory for Atmospheric Research, Greenbelt, Maryland, July 30, 1996 *(invited seminar)*.

Avissar, R., 1996. *The Impact of Landscape Heterogeneity on Atmospheric Dynamics.* Center for Weather Forecasting & Climate Research, National Space Research Institute, Sao Jose dos Campos, Brazil, August 8, 1996 **(invited seminar)**.

Avissar, R., 1996. *The Parameterization of the Atmospheric Planetary Boundary Layer in Numerical Limited Area Models.* ICTP/WMO Workshop, Trieste, Italy, October 21 - November 1, 1996 **(invited keynote speaker)**.

Avissar. R., 1997. *On the parameterization of subgrid-scale processes in atmospheric models.* Seminar, Tel Aviv University, Tel Aviv, Israel, January 7, 1997 **(invited)**.

Avissar, R., 1997. *At which scale landscape heterogeneity affects atmospheric dynamics.* Special Symposium on Boundary Layer and Turbulence. 77th American Meteorological Society Annual Meeting, Long Beach, CA, February 2-7, 1997 **(invited)**.

Avissar, R., 1997. *Scaling Land-Atmosphere Interactions: An Atmospheric Modeling Perspective.* International Association of Hydrological Science 5th Scientific Assembly, Rabat, Morocco, April 23 - May 3, 1997.

Avissar, R., 1997. *Scaling Land-Atmosphere Interactions.* Spring Meeting of the American Geophysical Union, Baltimore, Maryland, May 27-30, 1997.

Avissar, R., 1997. *Land-Atmosphere Interactions.* Summer Session of the Aspen Global Change Institute, Aspen, Colorado, July 7-17, 1997 **(invited keynote speaker)**.

Avissar, R., 1997. *An evaluation of the large-eddy simulation option of the Regional Atmospheric Modeling System (RAMS) in simulating a convective boundary layer: A FIFE case study.* 12th Symposium on Boundary Layers and Turbulence. Vancouver, BC, Canada, July 28 - August 1, 1997.

Avissar, R., 1997. *At which scale land-surface heterogeneity affects the convective boundary layer: Large-eddy simulations and wavelet analysis.* 12th Symposium on Boundary Layers and Turbulence. Vancouver, BC, Canada. July 28 - August 1, 1997.

Avissar, R., 1997. *A coupled large-eddy simulation and lagrangian particle dispersion model to study turbulence and dispersion in complex terrains.* 12th Symposium on Boundary Layers and Turbulence. Vancouver, BC, Canada. July 28 - August 1, 1997.

Avissar, R., 1997. *On the Parameterization of Turbulence in Microscale, Mesoscale, and Large-Scale Atmospheric Models.* Seminar, NASA-GISS and Columbia University (held jointly), New York, New York, September 12, 1997 **(invited)**.

Avissar, R., 1997. *Parameterizations and initial / boundary conditions in atmospheric models.* Symposium on Regional Weather Prediction on Parallel Computer Environments, Athens, Greece, October 15-17, 1997 **(invited keynote speaker)**.

Avissar, R., 1997. *A Wavelet Analysis of the Scales of Response of the Convective Boundary Layer to Land-Surface Heterogeneity.* Fall Meeting of the American Geophysical Union, San Fransisco, California, December 8-12, 1997.

Avissar, R., 1998. *On the parameterization of subgrid-scale processes in atmospheric models.* Seminar, SUNY at Stony Brook, New York, April 15, 1998 **(invited)**.

Avissar, R., 1998. *At which Scale Land-Surface Heterogeneity affects the Convective Boundary Layer.* Fall Meeting of the American Geophysical Union, San Fransisco, California, December 5-8, 1998.

Avissar, R., 1999. *An analysis of the impacts of land-surface heterogeneity on the dispersion of passive materials in the convective boundary layer using a coupled large-eddy simulation and lagrangian particle model.* 79th Annual Meeting of the American Meteorological Society, Dallas, TX, January 10-15, 1999.

Avissar, R., 1999. *An evaluation of the scale at which landscape heterogeneity affects the CBL with large-eddy simulations.* 79th Annual Meeting of the American Meteorological Society, Dallas, TX, January 10-15, 1999.

4 Appendices

4.1 Appendix A

Avissar, R., E.W. Eloranta, K. Gurer, and G.J. Tripoli, 1998. An Evaluation of the Large-Eddy Simulation Option of the Regional Atmospheric Modeling System in Simulating a Convective Boundary Layer: A FIFE Case Study. *J. Atmos. Sci.*, **55**, 1109–1130.

4.2 Appendix B

Avissar, R. and T. Schmidt, 1998. An evaluation of the scale at which ground-surface heat flux patchiness affects the convective boundary layer using a Large-Eddy Simulation model. *J. Atmos. Sci.*, **55**, 2666–2689.

4.3 Appendix C

Gopalakrishnan, S.G., S. Baidya Roy, and R. Avissar, 2000. An evaluation of the scale at which topographical features affect the convective boundary layer using large-eddy simulations. *J. Atmos. Sci.*, **57**, 334–351.

4.4 Appendix D

Baidya Roy, S., and R. Avissar. Scales of response of the convective boundary layer to land-surface heterogeneity. *Geophys. Res. Lett.*, **27**, 533-536.

4.5 Appendix E

Gopalakrishnan, S. and R. Avissar, 2000. Dispersion of passive materials in the convective boundary layer above heterogeneous landscape using large-eddy simulations and a Lagrangian Particle Dispersion Model. *J. Atmos. Sci.*, **57**, 352–371.